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M.W. Williams; W.T. Pfeffer & M. Knoll

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Final report:

COLLABORATIVE EXPERIMENT FOR PULSED RADAR VISUALIZATION OF WATER FLOW PATHS IN SNOW

M. W. Williams, W. T. Pfeffer, and M. Knoll

December 22, 2000

US Army Research Office: DAAD19-00-1-0367

Institution:
University of Colorado,
Boulder, Colorado.

INTRODUCTION

Movement of liquid water through snowpacks is one of the least understood aspects of snow hydrology [Richter-Menge and Colbeck, 1991]. It has an important influence on the timing and magnitude of snowmelt hydrographs [Caine, 1992] and on biogeochemical and geomorphological processes [Williams and Melack, 1989; Caine, 1995]. Adapting more physically-based approaches to understand and model flow through a snowpack should permit wider applications of operational snowpack models to more sites, and allow for year-to-year variability within a site [Melloh, 1999]. Similarly, research on glacial hydrology has shown that the least-understood part of this system is the simplistic way that current models treat meltwater storage and routing through supraglacial snowpacks [Arnold et al., 1998].

Movement of liquid water through snowpacks is generally recognized to occur in distinct flow paths rather than as uniform flow through a homogeneous porous medium. Seligman [1936] found that snowpack permeability was enhanced when flow channels were present in the snowpack. Oda and Kudo [1941] described flow fingers and flow along layer interfaces. Dye was used to trace flow paths during the Cooperative Snow Investigations [Gerdel, 1948; 1954; US Army, 1956]. Ice columns, described previously by Ahlmann and Tveten [1923], Ahlmann [1935], Seligman [1936], and Gerdel [1948], were recognized to be the residual flow network in cold snow by Sharp [1951]. Zones of preferential flow and ice columns have been observed in many other studies [e.g. Wankiewicz, 1976; Jordan, 1978; Denoth et al., 1979; Higuchi and Tanaka, 1982; Marsh, 1982 and 1988; Kattelmann, 1985 and 1986].

However, attempts to characterize the spatial distribution of preferential flowpaths have had only limited success [Marsh and Woo, 1985; Kattelmann, 1989; Kattelmann and Dozier, 1999]. Attempts to understand two-dimensional meltwater flow through snow from first principles have also had only limited success [Colbeck, 1979; 1991]. Overall, our ability to understand the spatial distribution of preferential flowpaths in melting snowpacks has suffered from the ephemeral nature of the flowpaths and the problems caused by destructive sampling of the snowpack [Schneebli, 1995; 1999; Albert et al., 1999].

Most methods of investigating meltwater flow through snow involve sparse or invasive sampling. This makes it difficult to study scale and time-dependent processes such as the evolution of preferential flowpaths. Ground penetrating radar may provide a non-invasive method of investigating preferential flow of meltwater through snow.

Imaging of internal snow pack properties using radar wavelengths shows promise as a non-invasive technique. The radar bandwidth has been used to detect surface and near-surface melting of snow [Koh, 1992; Koh and Jordan, 1995]. Radar reflection methods have been used to measure snowpack thickness and average water content [Annan et al., 1994]. Recently, Albert et al. [1999] demonstrated that flow paths in snow can be imaged by deploying radar antennas in snow trenches and orienting them so that they were most sensitive to reflections off vertical features. They were able to detect and map flow features as far as 1 m from trench faces using a Frequency Modulated Continuous Wave (FMCW) radar system in the 2-6 GHz range. Excavations confirmed that reflections were due to flow features in the snow pack. However the hydraulic properties of these flow features could not be determined without disturbing the snowpack.

Ground-penetrating radar (GRP) is a non-invasive geophysical technique that utilizes high-frequency (10 MHz-10 GHz) electromagnetic waves to image the subsurface [Davis and Annan, 1989]. In the past decade there has been a dramatic increase in the sophistication and number of GPR applications in hydrogeology, using both radar reflection profiling [Knoll et al., 1991; Peretti et al., 1999] and crosshole tomography [Hubbard et al., 1997]. Radar reflection profiling involves moving two, closely spaced, antennas together along a line and recording reflections from subsurface contrasts in dielectric properties. While this method is good for imaging sub-horizontal structures, it does not provide information on the material properties of a medium.

Crosshole radar tomography seems ideally suited to imaging and characterizing preferential flowpaths in snow. However, to the best of our knowledge it has never been applied to snow. Crosshole radar tomography involves inverting data from a multitude of transmission experiments with different source and receiver locations in two boreholes. The area between the

boreholes is subdivided into cells to form the tomographic model domain. An inversion process is used to search for a set of model parameters that satisfy the system of equations representing the tranmission experiments. In this way, crosshole tomography leads directly to material property estimates: the tomographic images also provide useful structural information. To illustrate, crosshole radar tomography has been used in hydrogeologic investigations to monitor the infiltration of fluids through the vadose zone, and to estimate soil hydraulic properties [Hubbard et al., 1997].

Here we report on a proof-of-concept experiment conducted to evaluate the potential of crosshole radar tomography to image and characterize preferential flowpaths in snow. The experiment was conducted at Niwot Ridge in the Colorado Front Range on 3 June 2000. We purposely chose difficult conditions for the test, a wet and draining late-season snowpack. Our objectives were: (1) to determine if the frequencies available for borehole antennas would be able to penetrate a wet and draining snowpack; (2) determine if their was sufficient change in the travel velocity of the radar waves to provide information on the material properties of snow; (3) to evaluate if "skipping" of radar waves at the snow/air interface would cause problems such that the technique could not be used: and (4) use this information to make an informed decision on the potential of crosshole radar tomography to image preferential pathways in seasonal snowpacks.

SITE DESCRIPTION

The experiment was conducted on the Niwot Ridge saddle at an elevation of 3,500 m, located in the Colorado Front Range of the Rocky Mountains about 5 km east of the Continental Divide (40° 03' N, 105° 35' W). This site is an UNESCO Biosphere Reserve and a Long-Term Ecological Research (LTER) network site. Climate is characterized by long, cool winters and a short growing season (1-3 months). Mean annual temperature is -3.8°C and annual precipitation is 1,000 mm [Williams et al., 1996]. About 80% of annual precipitation falls as snow [Caine, 1996].

The 2000 snow season at Niwot Ridge was characterized by below average snow deposition, a warm snow melt season with little precipitation, and early and continuous snow melt. By the first week of June about 80% of the seasonal snow pack had melted. The experiment was conducted on a snow patch with dimensions of 50 m x 100 m. Slope angle of the experimental site was about 5°, with a SSE aspect.

METHODS

Field experiment. The experiment using crosshole radar tomography was conducted using a pulse radar system with 250 MHz borehole antennas, the highest frequency available. A snowpit was dug to the ground, approximately 2 m^2 in area. A PVC pipe, 3" id, was inserted horizontally at the bottom of the snowpack, in 1-m increments. As each pipe segment was inserted at the bottom of the snow pack, snow was removed from the pipe using a Federal snow sampler. We successfully inserted 5 m of pipe horizontally along the bottom of the snowpack, running perpendicular to the fall line. A second PVC pipe, also 3" id, was then laid on the snowpack surface, parallel to the pipe at the bottom of the snowpack. The snowpack was undisturbed between the two pipes. The end coordinates of the two pipes were measured relative to the NW corner of the top pipe. This allowed us to assign a position in space to each radar measurement.

The antennas were attached to ropes marked every 0.1 m and placed in the pipes. The snowpits were then backfilled to minimize potential problems caused by the snow-air interface. The borehole antenna in the top pipe was pulled over a distance of 5.0 m, with a measurement every 0.1 m. The bottom antenna was then moved 0.1 m and the top antenna again moved over the tracking distance of 5.0 m with a radar measurement every 0.1 m. The procedure was then repeated until the bottom antenna had moved 3.5 m. The length of the borehole antenna was 1.5 m. Consequently, when we refilled the snow pit, we could only pull the bottom antenna a distance of 3.5 m. We were thus able to measure radar waves using crosshole radar tomography every 0.1 m for a distance of 3.5 m for the bottom antenna and 0.1 m for a distance of 5.0 m for the top antenna, a total of 1750 radar measurements with a variety of angles and crossing

patterns.

Physical properties of the snowpack were measured in a snow pit approximately 10 m from the experimental site. Liquid water content of the snow was measured using a Denoth Wetness Sensor [Denoth et al., 1984; Williams et al., 1999a]. Snow density was sampled using a 1-L stainless steel cutter in vertical increments of 10 cm [Williams et al., 1999b]. Temperature of the snowpack was measured every 10 cm with 20-cm long dial stem thermometers, calibrated to ± 0.2°C using a one-point calibration at 0°C.

RESULTS and DISCUSSION

Field Experiment

Weather during the radar experiment on 3 June 2000 was warm and sunny. The experiment was conducted between 1 and 3 pm. Air temperature at 1 m height above the snow field was 10°C. Wind was less than 2 m s^{-1}. Cloud cover was less than 10%.

The radar experiment appeared to work in the field. Snow depth at the radar site was approximately 150 cm. We were able to pull the 250 MHz antennas through the pipes with little problem. Real-time evaluation of the radar data in the field showed that we were receiving signals through the snow pack. More encouraging, there were differences in the wave speed of the first-arrival traveltimes for the crosshole data. These results showed that the 250 MHz radar waves were able to penetrate the snowpack, and that one or more material properties of the snowpack were causing differences in propagation of wave speeds through the snowpack.

Concurrent with the crosshole radar tomography experiment, we dug and analyzed a separate snow pit for snow properties. The analysis of the snow pit was conducted simultaneous with the radar imaging in a near-by location because the liquid water content can be expected to change during the day under warm and sunny meteorological conditions. Snow depth of the pit was 150 cm. The snow pack was isothermal at 0°C. Snow grains were type 6b [Colbeck et al., 1990], melt-freeze polycrystals formed when water in veins froze. Density ranged from 470 to

550 kg m^{-3}, with a mean of about 500 kg m^{-3}. The dielectric constant as measured by the Denoth meter and corrected for snow density ranged from 2.3 to 3.1. The liquid water content ranged from 1.5 to 4.5% by volume. Snow density, dielectric constant, and liquid water content were all lower in the bottom 30 cm of the snowpack. This lowest 30 cm of the snowpack was old depth hoar (crystal type 4a) which had undergone wet metamorphism but still retained properties characteristic of depth hoar.

Crosshole Radar Data Analysis

Travel velocities ranged by more than a factor of two, from about 125 m μs^{-1} to 300 m μs^{-1} (Figure 1). Note that in Figure 1, the area below the pipe is soil below the snowpack. These results show that there is also refraction of radar waves from frozen soil below a wet and draining snowpack.

The wavespeeds suggest some problems with the radar technique. The striping at the top and sides of the wavespeed figure suggest problems at the snow-air interface. Similarly, the large area of high wave speed on the right side of the figure is where the snow pit had been refilled. Air has a dielectric constant of 1 and a high velocity (300 m μs^{-1}). Consequently radar energy preferentially refracts through air rather than travel through the snow. The ray coverage needed for good tomographic inversion may be limited at the snow-air interface and also in snowpits that have been refilled. The quality of parameter estimates near the snow pits is thus suspect, but this doesn't affect results from the middle of the model, where we see the finger-like features extending down from the surface.

We then inverted the traveltime data to the dielectric constant for each grid cell using a curved ray traveltime tomography algorithm developed by Aldridge and Oldenburg [1993]. This algorithm reconstructs a two-dimensional velocity field from measured first arrival times by iteratively changing the model until the difference between observed and calculated traveltimes is reduced to an acceptable level. The inversion process includes a regularization matrix to stabilize the inversion process, perform a little spatial smoothing, and assign parameter values to cells

that don't have any ray coverage (such as slow zones avoided by refracting rays). The forward modeling of traveltimes was then accomplished by Vidale's [1988] finite-difference scheme.

Here we only show the region between 0.75 m and 4.25 m, to get rid of most of the edge effects and model cells with low ray coverage (Figure 2). In an effort to improve parameter estimates, we including some spatial constraints in the tomographic inversion process. We forced dielectric constant values in the air to have a value of 1. We then used as a reference model with K=1 values near where the snow pits to avoid local minima caused by extreme velocity contrasts near the edges of the models. These constraints help quite a bit, but the first constraint introduces a cyclical banding artifact in the upper 0.25 m that we haven't figured out how to eliminate yet.

Values for the calculated dielectric constant using crosshole radar tomography ranged from 1.0 to 4.0 (Figure 2). The range of these values is about twice that as measured by the Denoth Moisture Meter, which measured dielectric constants that ranged from 2.3 to 3.1. The crosshole radar tomography appears to measure reasonable values for the dielectric constant of undisturbed snow in a wet and draining snowpack.

SUMMARY

Our proof-of-concept experiment shows that crosshole radar tomography is a viable method for non-invasive imaging of the material properties of snow. Crosshole tomography is capable of penetrating a wet and draining snowpack and retrieving reasonable values for material properties such as density and liquid water content.

Natural processes should create generate some common geostastical and petrophysical characteristics for things like flow fingers and ice columns. We should be able to map these probablistically (i.e., soft data), some better than others. For instance, dry high-porosity (low density) zones should be easy to map in tomography. Similarly, flow fingers in a dry snowpack should be easy to map using crosshole radar tomography.

We suggest the following experiments to provide follow-up information on the use of cross-hole radar tomography to image preferential flowpaths. Ground penetrating radar will be used in three modes: (i) vertical boreholes analogous to established techniques in groundwater imaging; (ii) horizontal boreholes; and (iii) surface reflectance. For horizontal boreholes, 10 m lengths of 3" ID PVC pipe is placed on the ground prior to snowfall and the ends marked. When measurements are made, another pipe is placed on the snow surface. The borehole antennas (250 MHz) are then pulled through both pipes at 10 cm increments. Vertical boreholes are simpler, with the 3" PVC pipe inserted just prior to measurements, and interior snow removed with a Federal Sampler. The antennas are then lowered or raised at 10 cm increments. Repeat measurements over time are thus possible because the snow between the pipes is not disturbed. Biweekly GPR measurements will be taken at 3 undisturbed sites located near our lysimeters, using each of the 3 modes above.

Ground truthing of the radar tomography will be an important component of the radar experiments. Independent measurements of dielectric properties will be made at about the same scale as determined from the tomography. For each ground truth experiment, we will dig a snow pit in the middle of a horizontal radar tomography line. We will use a capacitance probe (Denoth moisture meter) to measure dielectric properties at closely spaced vertical points every 10 cm. Similarly, density and stratigraphy will be measured. Ground truth measurements will take two forms: (a) bi-weekly measurements of the natural snowpack from the initiation of liquid water infiltration into a dry snowpack through the melt season; and (b) bi-weekly irrigation measurements based on the method of Arthur et al. [1999], which simply consists of adding a known amount of water at a known rate sufficient to increase the volumetric liquid water content by a factor of 2 to 3. The irrigation studies will be analyzed in two modes: (a) destructive sampling after the tomography so that areas of high and low water content can be measured by hand; and (b) time-lapse fashion where we slowly add water throughout a day and look for tomographic changes as a function of time. We will also investigate different frequencies, such as using 250 MHz in the bottom borehole and 900 MHz surface penetrating radar at the snow surface.

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FIGURE CAPTIONS

FIGURE 1. Cross-sectional image of the radar wave velocities of a wet and draining snowpack. Black circles and stars show the transmitting and receiving antenna locations, respectively, within PVC pipes placed at the top and bottom of the snowpack. The bottom pipe extends into frozen soil at distances greater than 3 m.

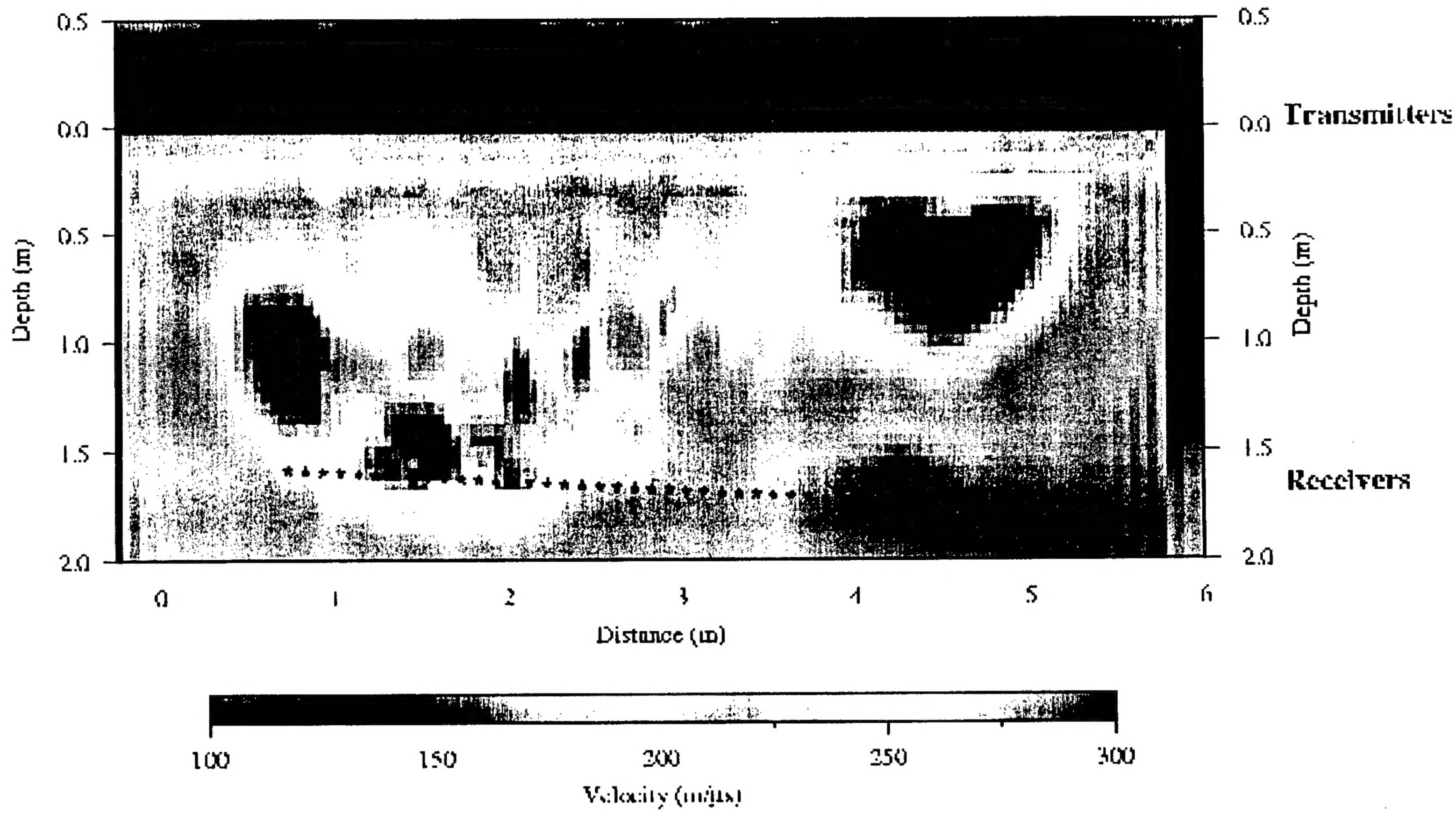
FIGURE 2. Cross-sectional image of the dielectric properties determined from tomographic inversion of crosshole radar traveltime data collected on Niwot Ridge on 3 June 2000. Note the dielectric constant values above 3 (greens mostly) at the top of the snowpack, and how these values connect up with localized zones of even higher dielectric constant values (yellows) at depths below 0.5 m; we interpret these funnel-shaped structures to be zones of high water content (i.e., preferential flow paths) within the late-stage snowpack.

Niwot Ridge GPR Tomography

Eikonal Algorithm

15 Tomographic iterations | 0.10 ns picking error | Regularization - flatness (20, 10)

25 LSQR iterations | 0.05 m grid spacing | Velocity models (ref, init)



GMT Nov 27 11 10 38 2000 /data/SnowPronto-Vel.gmt

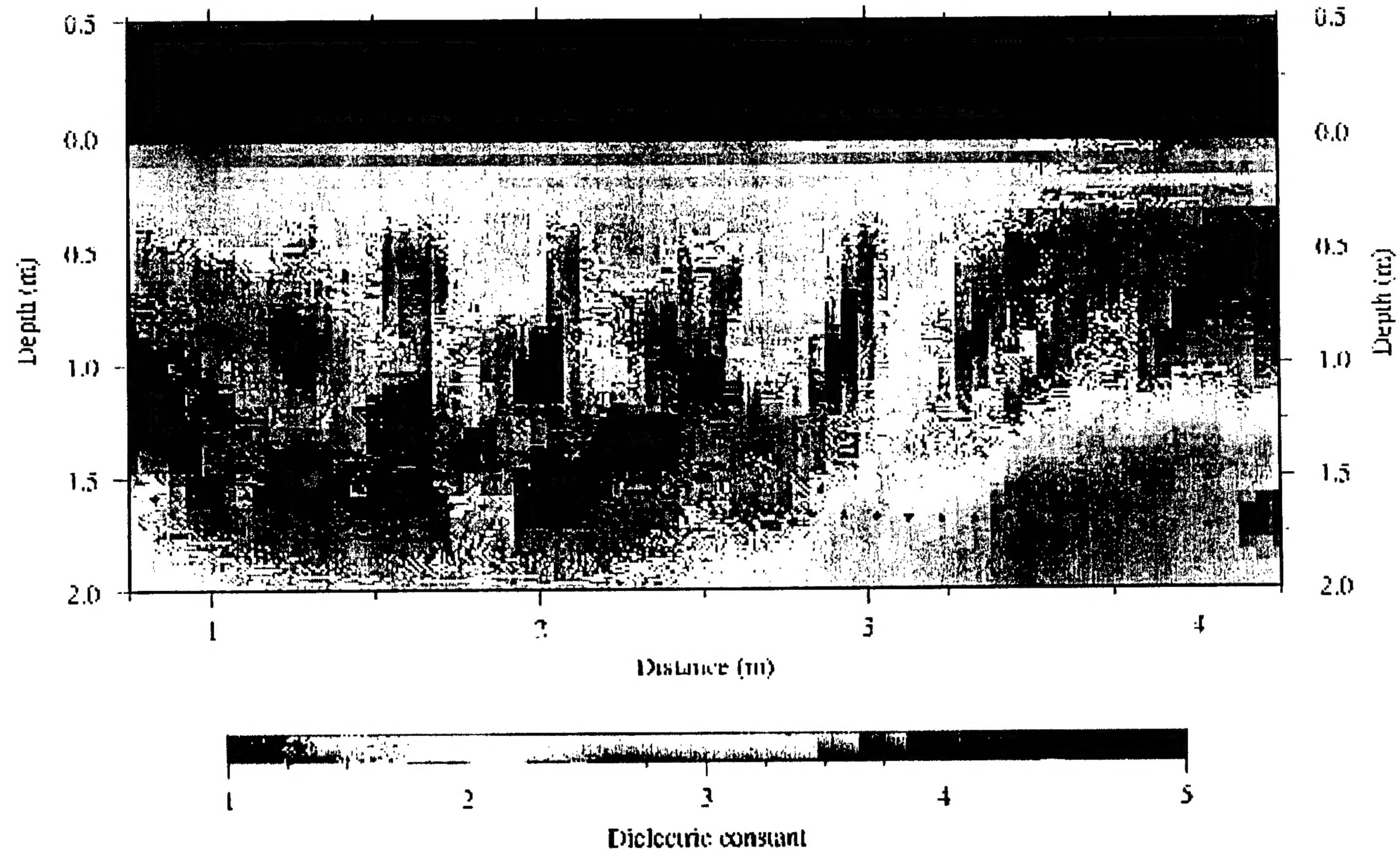
Niwot Ridge GPR Tomography

Eikonal Algorithm

15 Tomographic iterations
25 LSQR iterations

0.10 ns picking error
0.05 m grid spacing

Regularization - flatness (10, 10)
Velocity models (ref, int)



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